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ABSTRACT

This article describes a visual interactive decision support system for the simultaneous location of several rapid transit lines in a city. Three types of tool are available to the user: parameter setting, menu choices, and mouse operations. The system produces network configurations of the type selected by the user and computes a number of effectiveness measures. The system has been tested on real data from the city of Milan, Italy. It can consistently produce several interesting alternative solutions within short computing times.

Keywords : rapid transit network configurations, heuristics, visual interactive decision support systems.

RÉSUMÉ

Cet article décrit un système d'aide à la décision visuel interactif pour la localisation simultanée de plusieurs lignes de transport rapide dans une ville. Les utilisateurs disposent de trois types d'outil : détermination de paramètres, choix de menus et mouvements de souris. Un système produit des configurations de réseau du type choisi pour l'utilisateur et calcule diverses mesures d'efficience. Le système a été testé sur des données réelles provenant de la ville de Milan en Italie. Il peut produire avec fiabilité plusieurs configurations intéressantes moyennant des temps de calcul raisonnables.

Mots clefs : configurations de réseaux de transport rapide, heuristiques, systèmes d'aide à la décision visuels interactifs.

1 Introduction

Over the last decades, several major cities throughout the world have resorted to the construction of rapid transit systems as a means of decreasing traffic congestion and enhancing mobility. Due to the prohibitive cost of traditional underground networks, there has been a shift toward less expensive light railways, some of which make use of innovative engineering technologies. The design and construction of such systems are major undertakings that involve the participation of several players including different levels of government, engineers, planners, financial institutions, environmentalists, political lobbies, etc. Large capital expenditures and operating costs are at stake and the level of risk is important. Careful planning is therefore critical in this context. Rapid transit systems play a major role in urban and regional development and affect many peoples' lives on a daily basis. The criteria used for network design are numerous and to some extent fuzzy. Typically compromises must be reached between cost and public benefits, and these are often difficult to measure and compare. In addition, a number of positive and negative externalities come into play, such as impacts on real-estate and retail prices, socio-economic activities, architectural heritage, impact on parking, atmospheric, noise and visual pollution, etc. (see, e.g., Gendreau, Laporte and Mesa [1], Stone et al. [2], Jiménez Solano [3], and Bay [4]).

The determination of a final design is normally reached after a lengthy and complex negociation process during which several options are examined, evaluated, and modified. Thus the problem cannot be cast as a standard single-objective optimization exercise nor is it appropriate to produce a single solution. Decision markers must be presented with a large number of good quality solutions to choose from [5]. While the decision making process is to a large extent political, it can be enhanced by the use of operational research techniques. In recent years research efforts have focused on two main areas: the definition of indices and measurements allowing the assessment and comparison of various transit network configurations (Musso and Vuchic [6], Laporte, Mesa and Ortega [7,8]), and the development of heuristic methods for the location of a single alignment (Dicesare [9], Dufourd, Gendreau and Laporte [10], Bruno, Ghiani and Improta [11], Bruno, Gendreau and Laporte [12]). To our knowledge, the multi-alignment problem has never been tackled by operational research methods.

The aim of this short article is to devise an automated method for the multi-alignment transit network design problem. It extends a previous algorithm of Bruno, Gendreau and Laporte [12] for the single alignment case. The proposed method can quickly produce several good quality scenarios which can be assessed by means of any

available cost and efficiency measure. It has been embedded within a visual interactive support system that allows experimentation. Three types of tool are available to the user: parameter settings, menu choices, and mouse operations.

The remainder of this article is organized as follows. The algorithm and the evaluation measures for a single alignment are summarised in Section 2, while their extension to the multi-alignment problem are described and illustrated in Section 3. A conclusion follows in Section 4.

2 Single-alignment heuristic

The multi-alignment heuristic presented in this article builds upon single alignment heuristic developed by Bruno, Gendreau and Laporte [12] whose main features we now recall. The single alignment heuristic locates a transit line composed of a given number n of stations on a grid network under minimum and maximum inter-station spacing constraints ($\ell_{\min}$ and $\ell_{\max}$), with the objective of maximizing the total population covered by the alignment. In practice, $\ell_{\min}$ is close to 0.5 km and $\ell_{\max}$ is around 2 km.The model assumes that all population is located at vertices of the grid network and the overall population coverage of an alignment is obtained by adding up the individual coverage of all stations, under the hypothesis that the catchment areas of any two stations do not overlap. The coverage of station s is defined as

$$C(s) = \sum_{k=0}^{k_{\max}} \sum_{(x,y):D[(x,y),s]=k} \theta_k p(x,y), \tag{1}$$

where (x, y) are the integer coordinates of a vertex of the grid network, $[D(x, y), s]$ is the Manhattan distance between (x, y) and s, $p(x, y)$ is the population at vertex (x, y), and the θ coefficients indicate the proportion of the population at vertex (x, y) likely to use the transit system. In our experimentations we have used $k_{\max} = 3, \theta_0 = 1, \theta_1 = 1, \theta_2 = 0.5, \theta_3 = 0.25$. Since a Manhattan metric is used, the value of $C(s)$ is obtained by summing up population values with decreasing weights located on concentric diamonds around s. The coverage measure can of course be defined differently if the context warrants it.

The location of a single alignment is performed in two main phases. In a construction phase, the procedure gradually extends a feasible alignment by adding at each step an additional station providing the maximal population coverage while respecting the inter-station constraints. In a post-optimization phase, an attempt is made to improve upon the best known alignment by keeping a truncated alignment of r consecutive stations, and attempting to relocate in a better way the remaining $n - r$

extremal stations, where r is a user-controlled parameter. Reconstructing the alignment from r to n stations is done as in the construction phase. For a given truncated alignment, several reconstruction attempts are made and the best is retained.

3 Multi-alignment heuristic

The single alignment heuristic just described has been extended to the case of several intersecting alignments. In the multi-alignment heuristic, the user must first select a configuration type from a menu of possible options. We have worked with eight of the basic configurations described by Laporte, Mesa and Ortega [7] : cartwheel, star, U and cross, circumferential, grid, triangle, half-wheel, half-radial (see Figure 1). Each of these configurations contains several *components* consisting of circles (in the case of the cartwheel and circumferential designs), and lines, some of which may be curved (as in the U and cross and the half-wheel designs). Each component corresponds to a distinct transit line. The networks depicted in Figure 1 only represent some of the options available to the user. By using the *customize* command, one can create other networks that combine circles and lines differently. Using a city map displayed on a screen, the user then specifies with the mouse a corridor (typically rectangular, circular or U-shaped) in which each component must be located. For example, Figure 2 depicts two intersecting rectangles for a star configuration made up to two lines. An interchange station is then tentatively located wherever two corridors intersect. Figure 2 contains a single interchange station identified by an eye icon. The user also specifies the number of stations and the inter-station spacing constraints for each line (Figure 3) and can permanently fix with the mouse the location of a number of stations corresponding to major destinations (e.g., universities, hospitals, shopping centers, etc.). The system incorporates a feasibility check ensuring that inter-station spacing constraints can be satisfied for each line, given the number of stations on the line. If an infeasibility is detected, a message appears on the screen asking the user to make a different choice. Fixed stations are shown by asterisks in Figure 2.

The location of each line is then determined separately using the procedure described in Section 2. However, because of the interaction between the lines care must be taken to preserve feasibility on all lines whenever a station is relocated. Of course moving an interchange station directly affects all lines on which it is located. One interesting feature of the system is the erase command activated by the eraser button, which enables the removal and reconstruction of an alignment segment between two specific stations using the mouse. Figure 4 illustrates the final configuration of cartwheel design in the city of Milan, Italy.

While the algorithm attempts to maximize the population coverage of the network, the system also provides other efficiency indicators that can help the decision

maker choose from among several good solutions. We have worked with the passenger/network effectiveness and the passenger/plane effectiveness coefficients introduced by Laporte, Mesa and Ortega [7].

The passenger/network coefficient measures the relative effectiveness of traveling by public transit instead of using another mode (e.g., a car). To define it, first consider the estimated number trips d_{ij} between stations i and j, t_{ij}, the shortest travel time between i and j on the public transit network (including waiting, travel and changing time) and τ_{ij}, the shortest travel surface transportation time (e.g., by car) between i and j. Then the passenger/network effectiveness measure is

$$\lambda = \left(\sum_{i<j} d_{ij} t_{ij} / \sum_{i<j} d_{ij} \tau_{ij} \right). \tag{2}$$

Typically, λ is larger than 1 since travel by public transit is less direct than surface travel. A low value of λ is a desirable feature of a transit system.

The passenger/plane effectiveness coefficient measures how well the network is embedded in the plane. Thus in a Manhattan type city, a grid network in which each line follows a street is perfectly embedded. If lines are diagonal with the respect to the streets, the level of embeddedness is low. This measure is important to the extent that rapid transit lines in cities often follow major streets. This measures depends on a metric ℓ_p that best describes the street layout. In a Manhattan type city, p would be close to 1. Denote by ℓ_{qij} the shortest travel time in the plane between i and j using an ℓ_q norm, as well as the two matrices $M_q = (d_{ij}\ell_{qij})$ and $\Theta = (d_{ij}t_{ij})$. Then the passenger/plane effectiveness coefficient is

$$\rho = \|\Theta - M_q\| / n, \tag{3}$$

where $\|.\|$ is the Frobenius norm, i.e., if $H = (h_{ij})$ is a matrix, then $\|H\| = \left(\sum_i \sum_j h_{ij}^2 \right)^{1/2}$. Again a low value of ρ is desirable. Laporte, Mesa and Ortega [7, 8] have observed that circumferential and cartwheel configurations yield relatively low passenger/plane effectiveness indices.Laporte, Mesa and Ortega [8] have proposed a procedure for the determination of the d_{ij} values, using a logit formulation for modal split distribution (see, e.g., Ortuzár and Willumsen [13]).The determination of q is usually achieved through the use of a statistical fitting method. A value around 1.5 is typical of many cities. Travel times τ_{ij} can be computed using a equilibrium algorithm (e.g., EMME/2 [14]), while transit times t_{ij} and ℓ_{pij} values are relatively straightforward to determine.

The system was extensively tested and we are highly satisfied with its robustness and flexibility. The underlying single alignment location algorithm consistently produces optimal or near-optimal solutions within very short computing times (see

Bruno, Gendreau and Laporte [12]), and its adaptation to the multi-alignment case appears to work just as well. The algorithm itself is extremely quick since it requires only one or two seconds per alignment on a Pentium 600. Producing graphical displays takes slightly longer but the overall time required for a typical problem rarely exceeds three or four minutes. In practice, the most time consuming operation consists of entering the data. Since the executing speed of the algorithm is high, users can easily perform several rounds of experimentation in a short time. The system was applied to real data from the city of Milan (ISTAT [15]) and has consistenly yielded high coverage solutions for a wide variety of configurations.

4 Conclusion

The design of rapid transit networks is a hard multicriteria problem involving a complex decision making process. Contrary to what happens in other contexts, optimality is ill-defined and several good solutions must be produced in order to make a final choice. Operations research techniques can be applied to assist the decision making process but they are in no way a substitute for it. The interactive decision support system we have developed can be used to produce a large set of candidate configurations. It is quick, robust and flexible, and the user can intervene at several stages to influence the shape of the solutions.To our knowledge the system we have developed is the first of its kind and we believe it can be of great help to practitioners.

Acknowledgements

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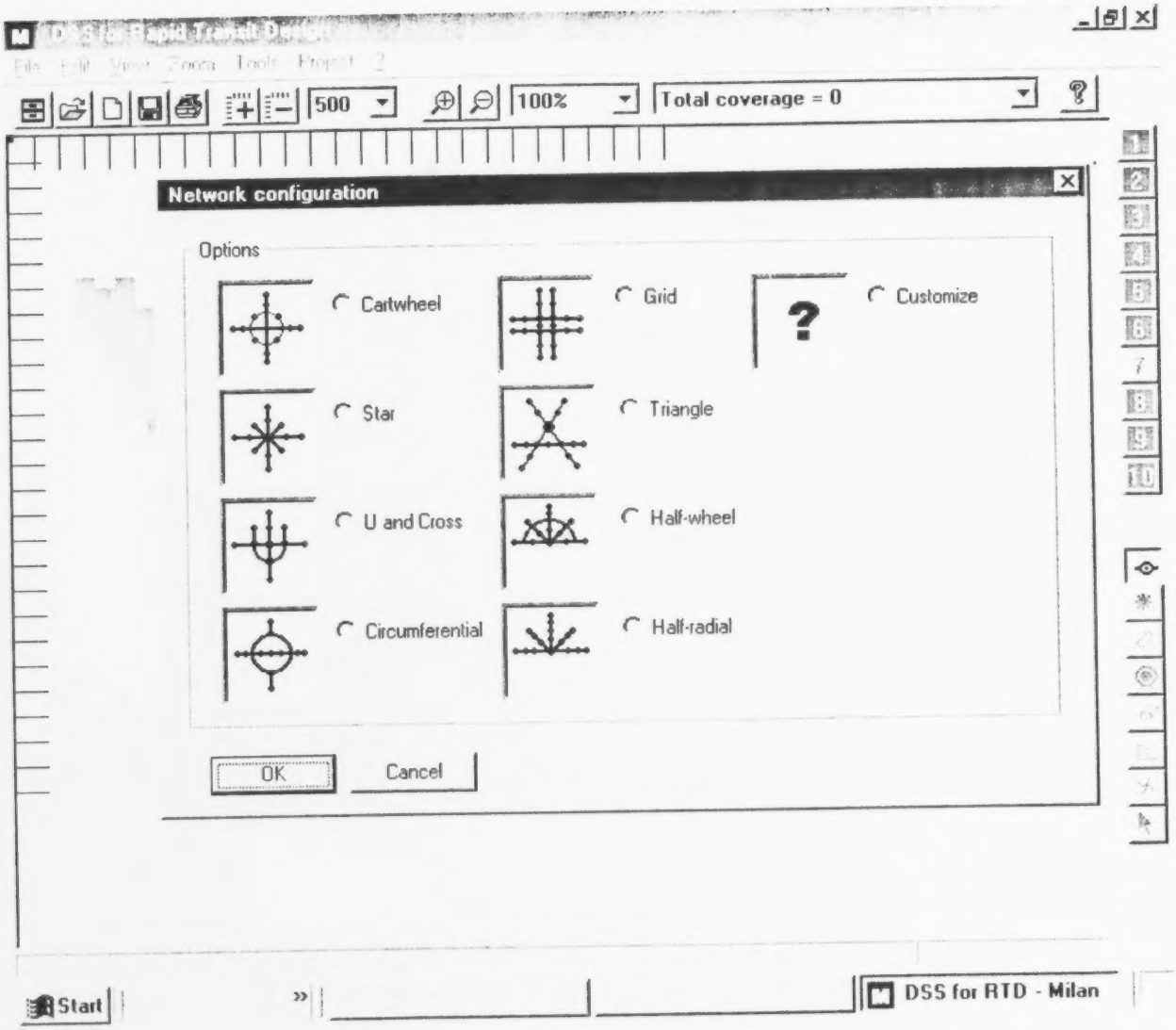

Figure 1 - Eight basic configurations

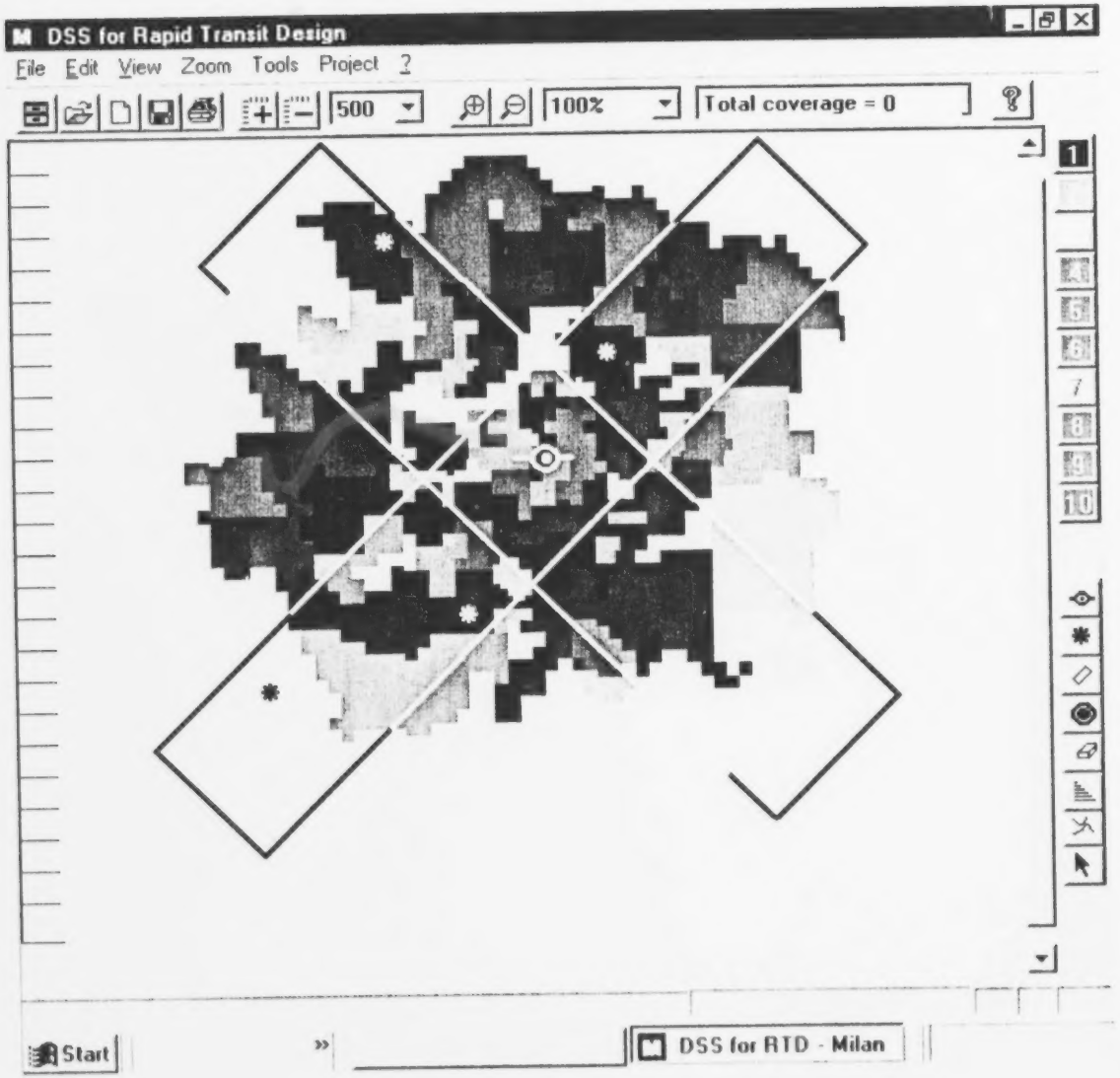

Figure 2 - Corridors for the two lines of a star configuration

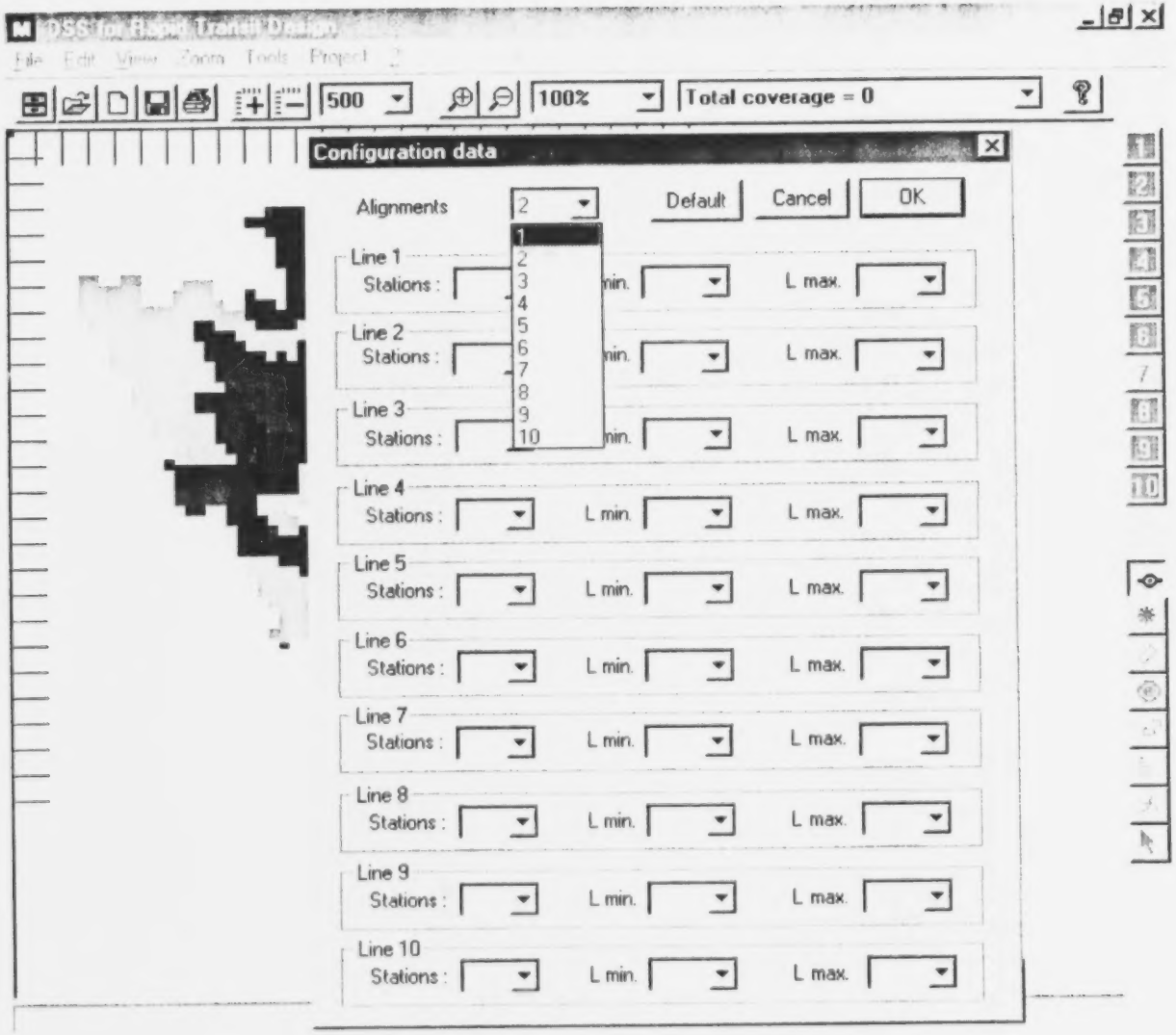

Figure 3 - Specifying the number of stations and inter-station constraints for each alignment

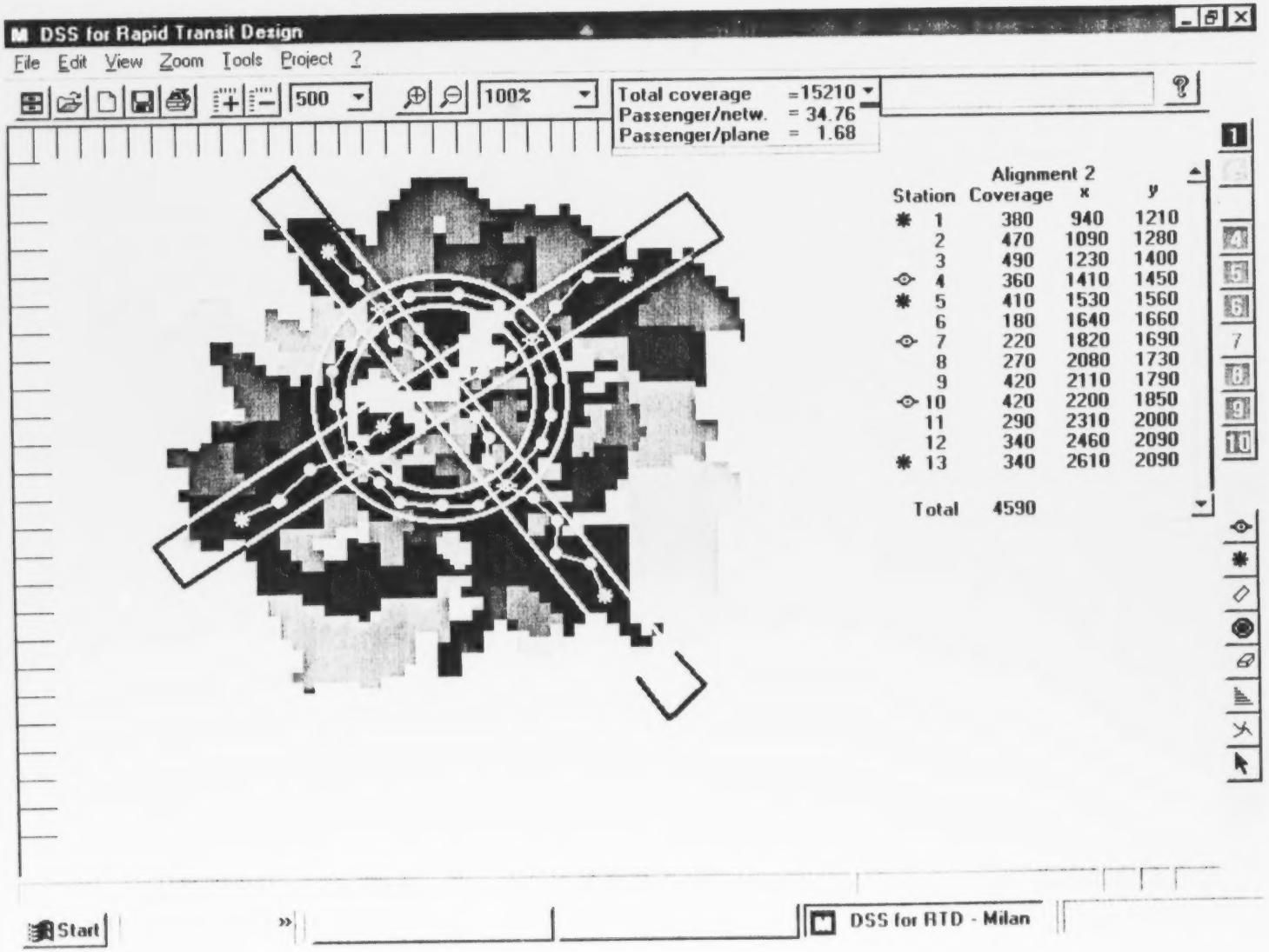

Figure 4 - Example of a final configuration for a cartwheel design